Measurements of the Neutron Structure Functions

Introduction

Most of the existing nucleon structure data - from elastic form factors to deep inelastic structure functions - come from decades of experiments on readily available proton targets, measurements on the neutron are essential for a complete understanding.

A complete determination of the valence content of the nucleon can be achieved only when both its u and d quark distributions are known.

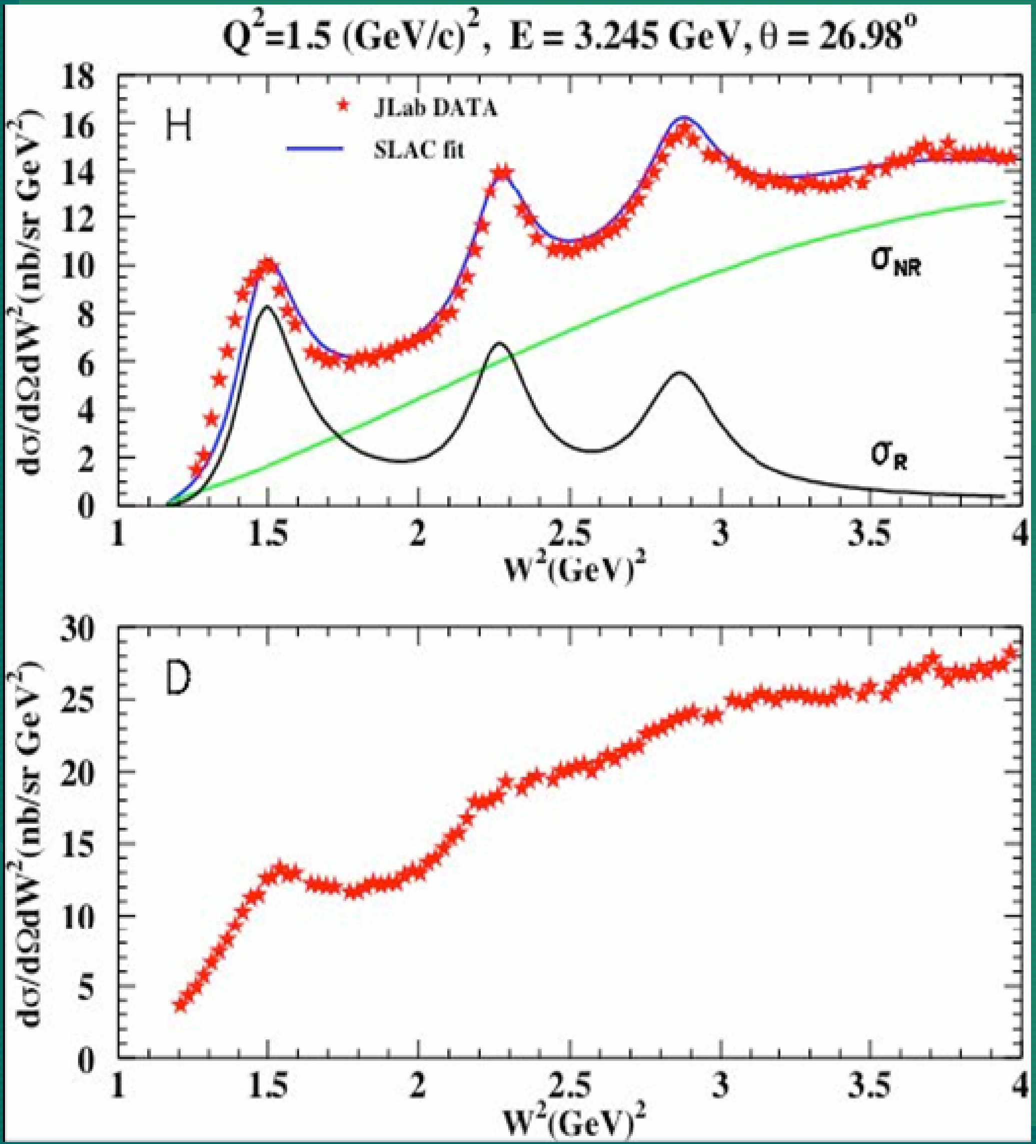
The absence of free neutron targets has meant that, until now, the usual method for extracting neutron structure information has been to use deuterium targets, and apply nuclear corrections arising from the Fermi motion and binding of the nucleons in the deuteron.

But, nuclear model uncertainties can be rather large. As a result, our knowledge of the structure of the neutron, especially in the neutron resonance region, and in the deep inelastic region at large x, is inadequate.

Physics Motivation (Neutron Resonance Structure)

Almost nothing is known about the nature of the resonance excitations of the neutron !!!

The three prominent resonance enhancements are obvious in the hydrogen data, but only a hint of the first (the Δ(1232)) is identifiable in the deuterium data. At $Q^2 > 2$ GeV^2, no discernible structure remains in the deuterium data at all. Neutron extraction from such data requires careful modeling of the resonant and non-resonant components for the neutron (as was done with the hydrogen data). Calculations must account for the nuclear effects of binding, Fermi motion, and nucleon off-shellness, and the model-dependence introduced by each of these steps leads to a substantial uncertainty in the neutron resonance structure functions.



Physics Motivation (Deep Inelastic Scattering at Large x)

For x >0.4 the contributions from the qq sea are negligible, and the structure functions are dominated by the valence quarks.
Knowledge of the valence quark distributions of the nucleon at large x is vital for several reasons.

1. The simplest SU(6) symmetric quark model predicts that the ratio of d to u quark distributions in the proton is 1/2, however, the breaking of this symmetry in nature results in a much smaller ratio. Various mechanisms have been invoked to explain why the d(x) distribution is softer than u(x).

2. If the interaction between quarks that are spectators to the deep inelastic collision is dominated by one-gluon exchange, for instance, the d quark distribution will be suppressed, and the d/u ratio will tend to zero in the limit $x \to 1$, This assumption has been built into most global analyses of parton distribution functions, and has never been tested independently.

3. On the other hand, if the dominant reaction mechanism involves deep inelastic scattering from a quark with the same spin orientation as the nucleon, as predicted by perturbative QCD counting rules, then d/u tends to 1/5 as $x \to 1$. Determining d/u experimentally would therefore lead to important insights into the mechanisms responsible for spin-flavor symmetry breaking.

Physics Motivation (Deep Inelastic Scattering at Large x)

Because of the 4:1 weighting of the squared quark charges between the up and down quarks, data on the proton structure function, F_2^p , provide strong constraints on the u quark distribution at large x:

$$F_2^p(x) = x\sum_q e_q^2\left(q(x)+\bar{q}(x)\right) \approx x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

The determination of the d quark distribution, on the other hand, requires in addition the measurement of the neutron structure function, F_2^n. In particular, the d/u ratio can be determined from the ratio of neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4\dfrac{d}{u}}{4+\dfrac{d}{u}}$$

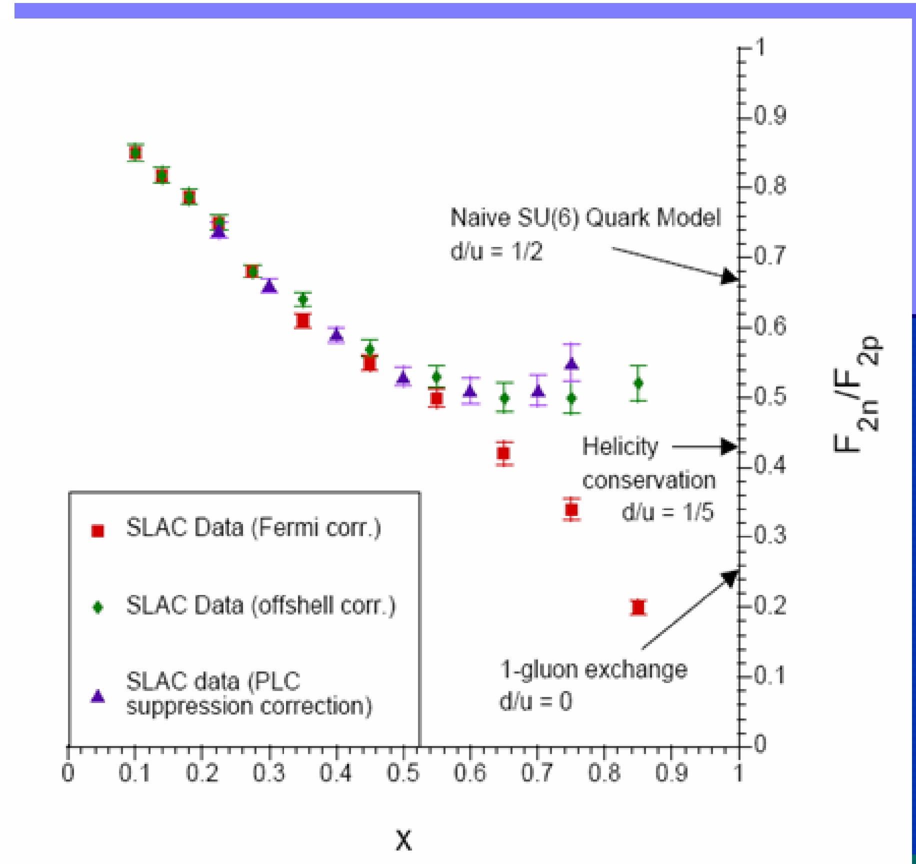
For, x > 0.4, so that the sea quarks can be neglected.

Physics Motivation (Deep Inelastic Scattering at Large x)

✓ **Proton Structure Function F_2^p measured very accurately.**

✓ **Neutron Structure Function F_2^n have been extracted from inclusive scattering off deuterium.**

✓ **Theoretical uncertainties in the treatment of nuclear corrections (Fermi motion, nucleon off-shell correction) can lead to values for F_2^n/F_2^p which differ by 50% at x=0.75, and by a factor ~2-3 at x=0.85.**

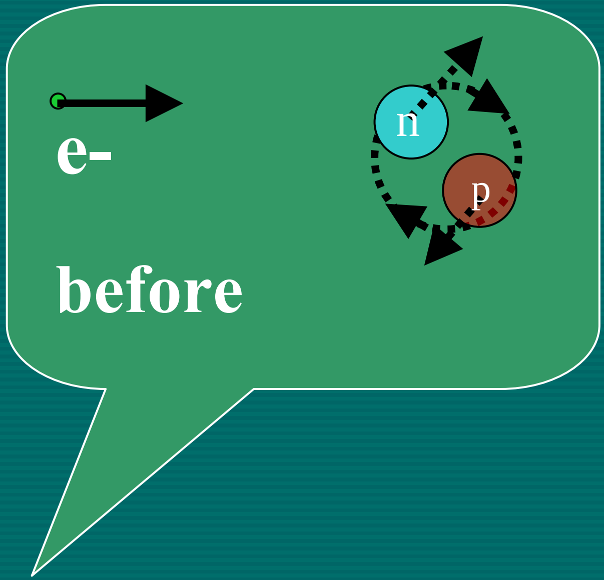


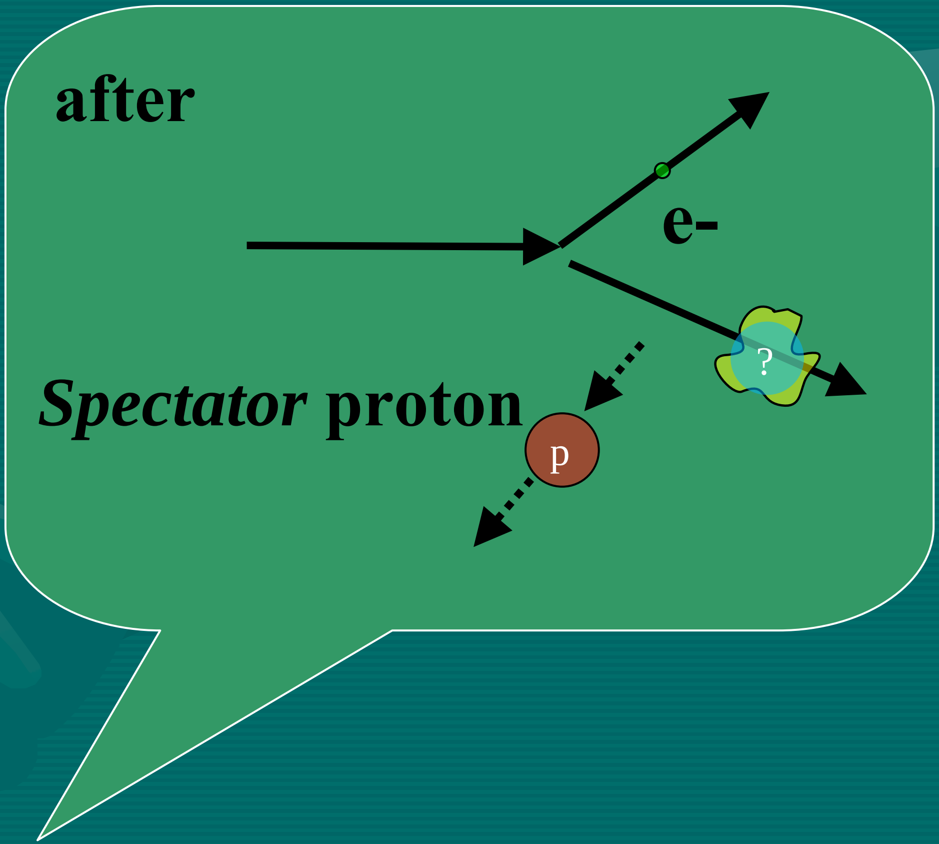
$$\frac{F_2^n}{F_2^p} \approx \frac{1 + 4\frac{d}{u}}{4 + \frac{d}{u}}$$

For, x > 0.4, so that the sea quarks can be neglected.

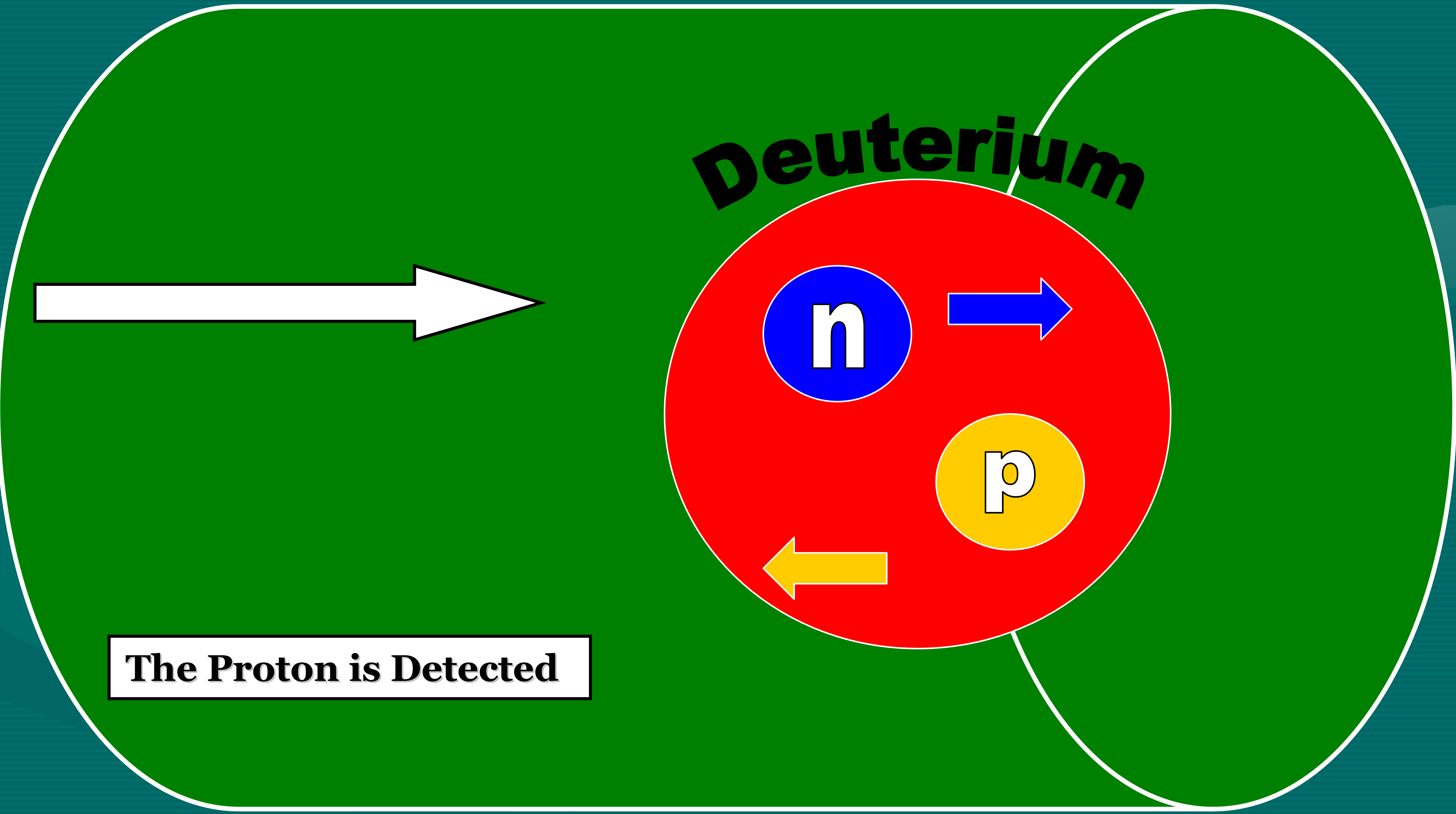
So, the measurements of the Neutron Structure Function F_2^n will eliminate the uncertainties from nuclear models !!!

The BoNuS Approach: An Effective Free Neutron target from Deuterium



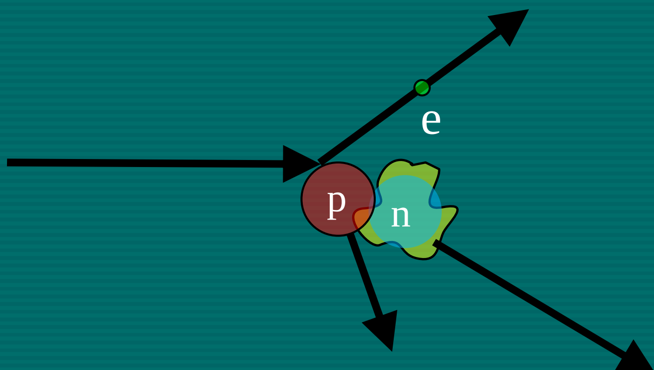


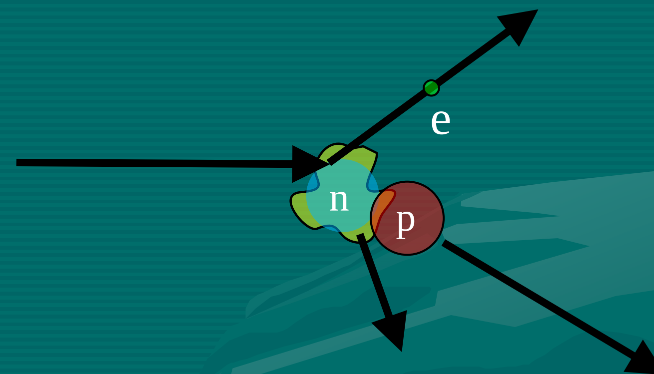
The BoNuS Approach: An Effective Free Neutron target from Deuterium



The BoNuS Approach: An Effective Free Neutron target from Deuterium

If the proton is going <u>backwards</u> in the lab frame, it is almost guaranteed to be only a spectator.

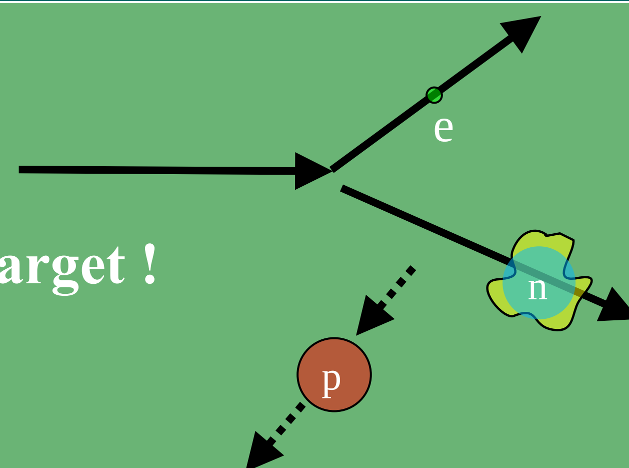




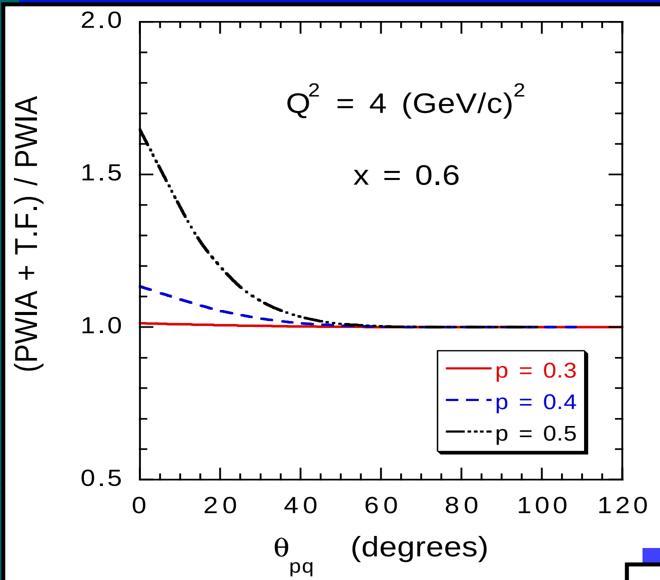
proton target <-- ambiguous --> neutron target

Measurement of the structure Function F_2^n on nearly free neutrons in the reaction $e^-d \to e^-pX$ by measuring the slowly backward moving recoil proton with the momentum below 100 MeV/c.

neutron target !



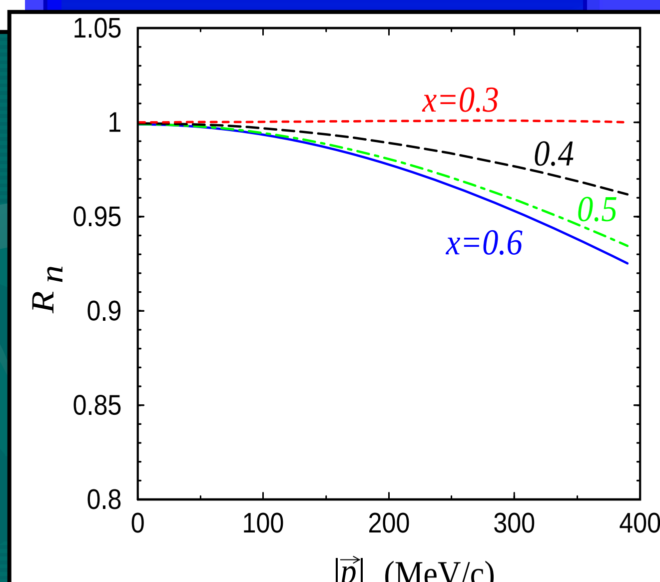
Backgrounds (Choice of Spectator Momentum and Angle)

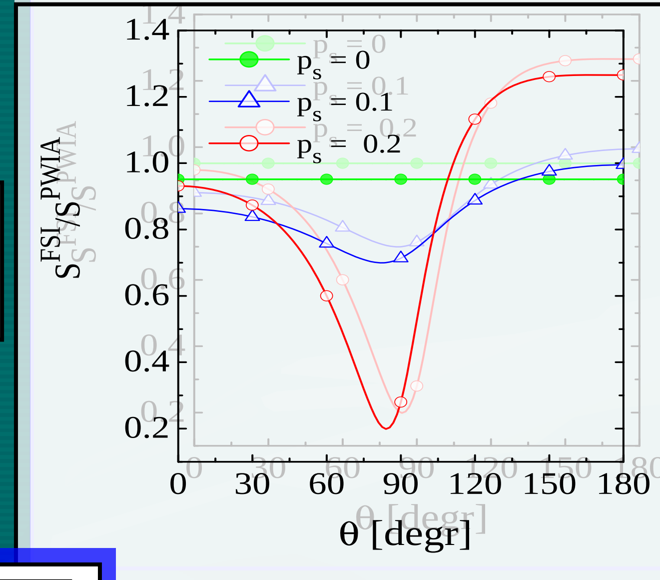


PWIA - plane wave impulse approximation (PWIA)

Target fragmentation negligible for θ_{pq}> 90

Ratio of Bound / free neutron structure Functions *O* (1%)

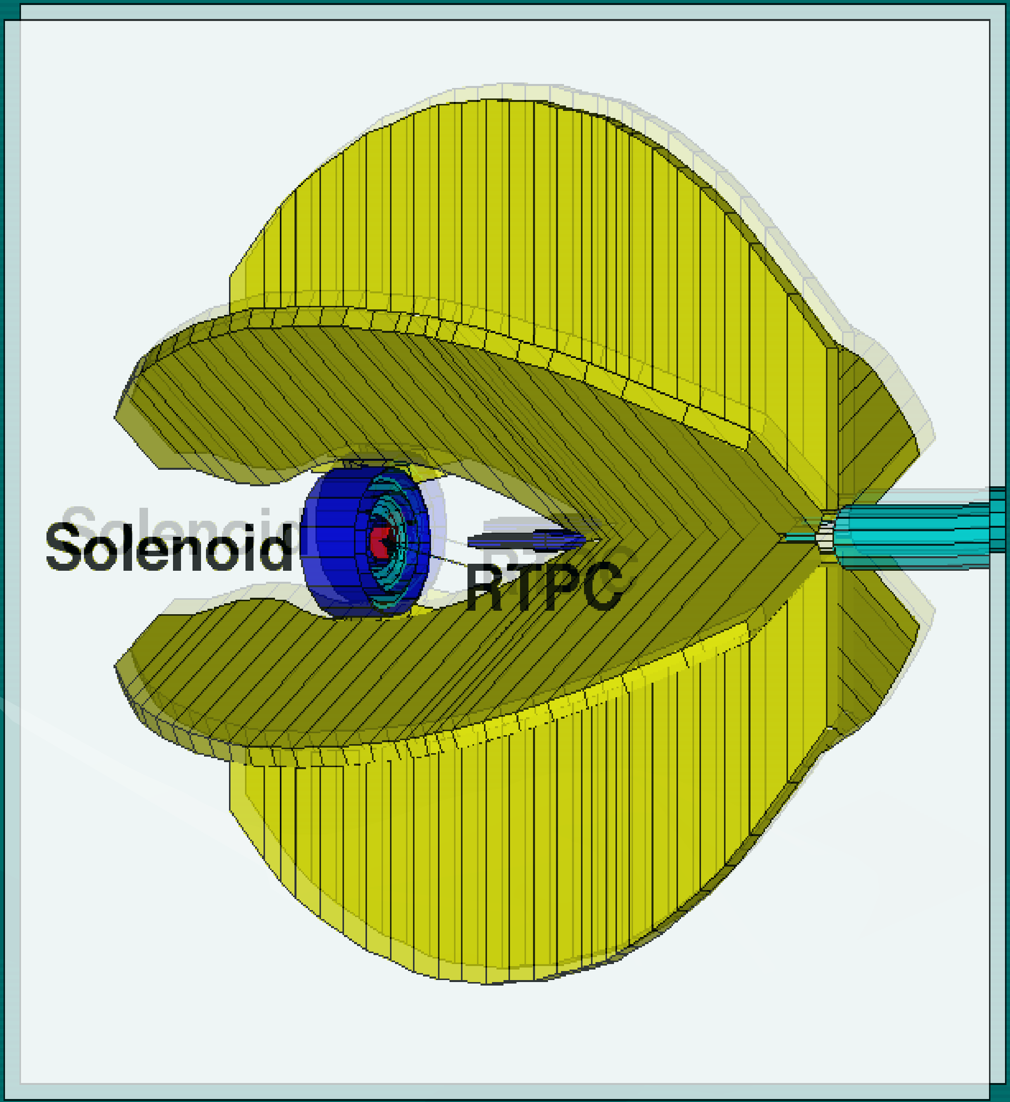




Another possible source of uncertainty arises from final state interaction (FSI) effects, or rescattering of the spectator proton by the deep inelastic remnants, X, of the scattered neutron.

Final state interactions *O*(5%)

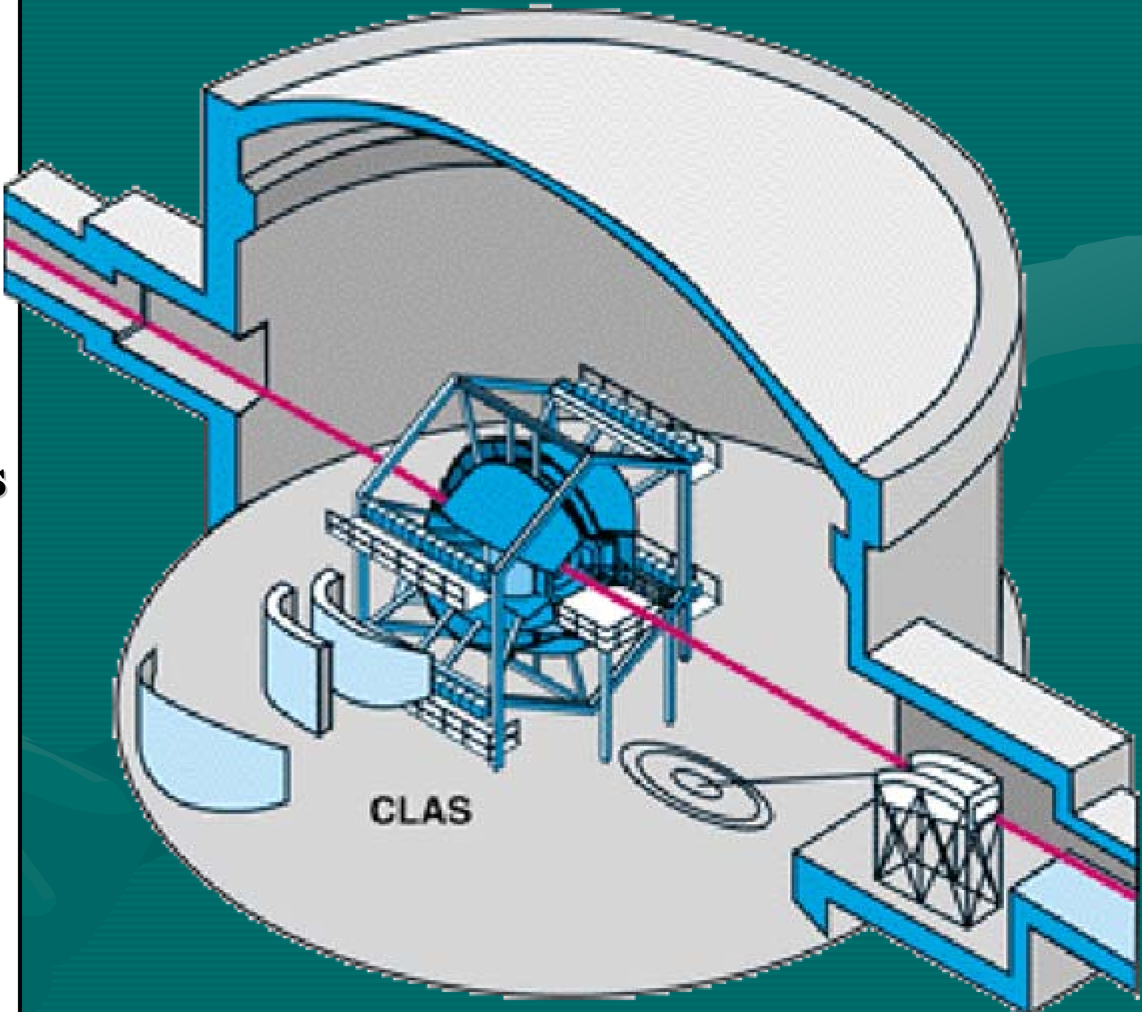
Experimental Setup

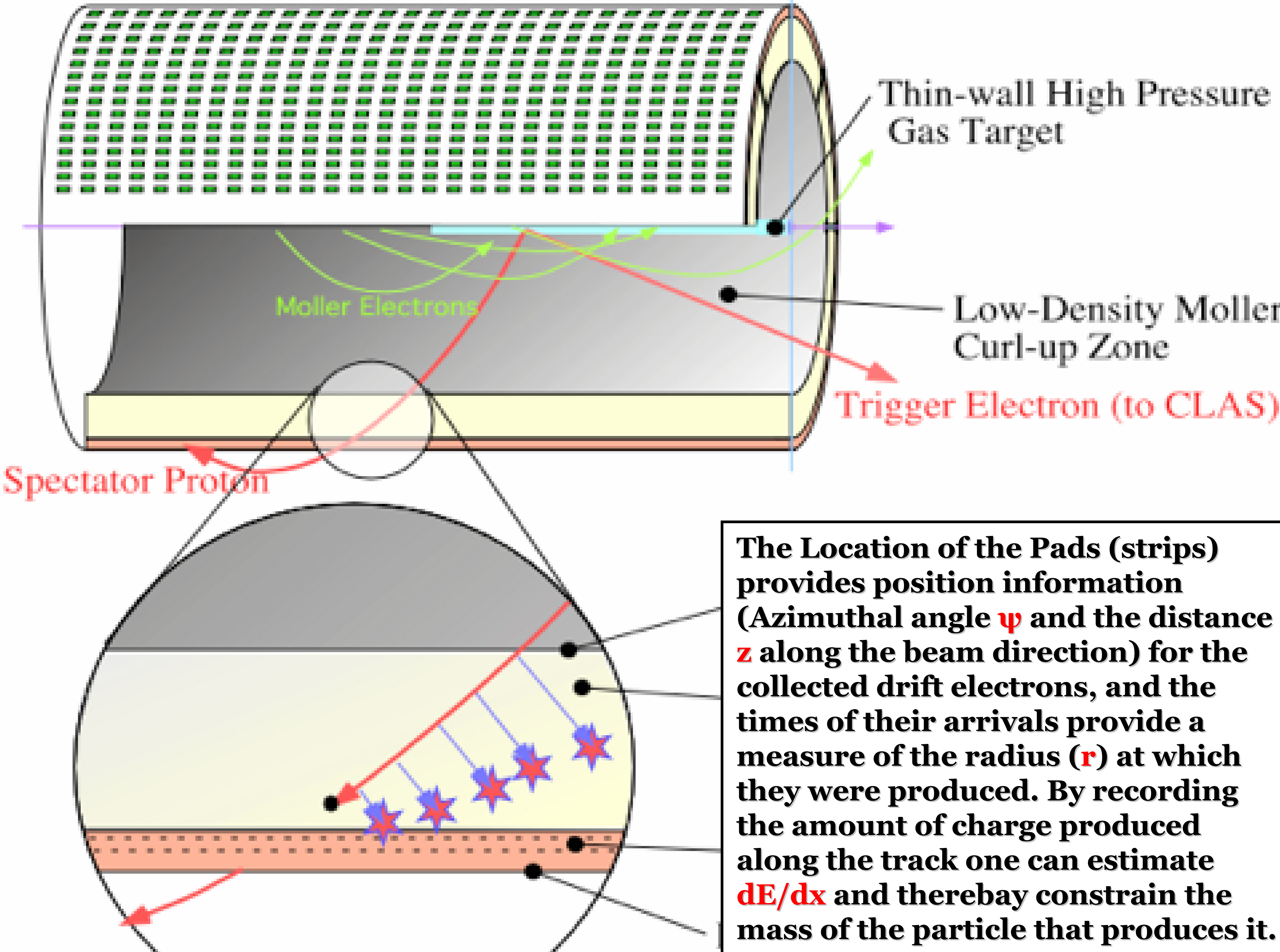


- Hall B CLAS spectrometer for electron detection
- Thin deuterium target (7.5 atm gas)
- Radial Time Projection Chamber (RTPC) for spectator proton detection
- DVCS solenoid to contain Moller background

CEBAF Large Acceptance Spectrometer (CLAS)

- Nearly 4π Acceptance
- Beam ~10 nA
- Cerenkov Counters
- Drift Chambers
- Forward Calorimeters
- Main Torus Magnet
- Large-Angle Calorimeters
- Data Acquisition
- Time-of-Flight System



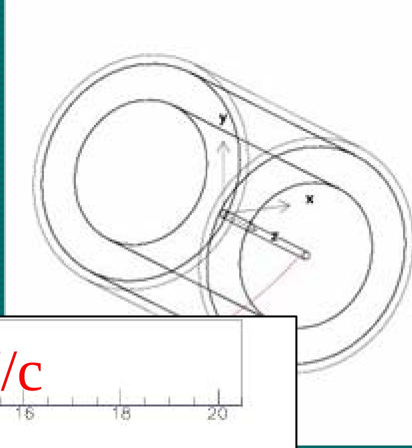


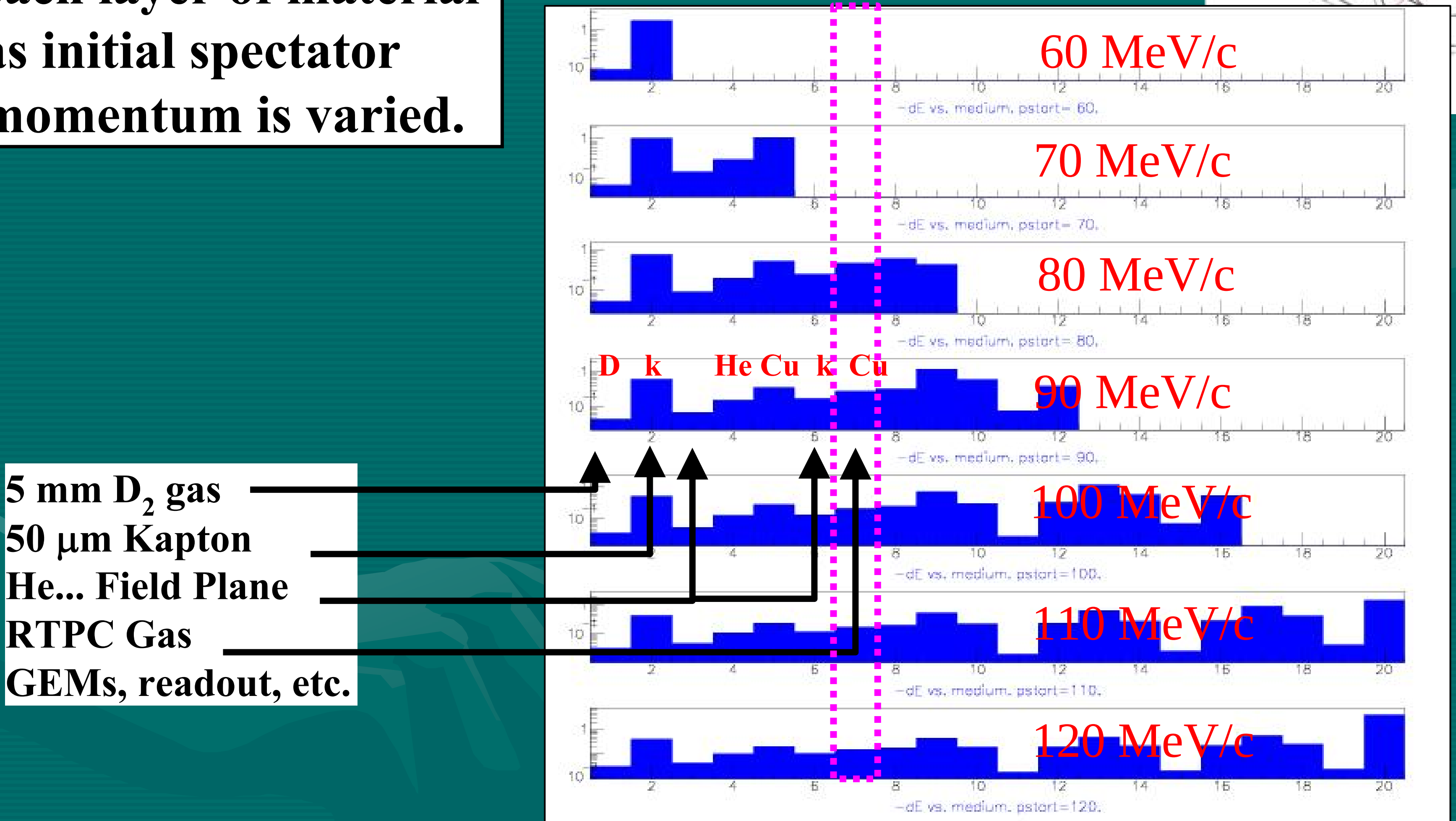
The Location of the Pads (strips) provides position information (Azimuthal angle ψ and the distance z along the beam direction) for the collected drift electrons, and the times of their arrivals provide a measure of the radius (r) at which they were produced. By recording the amount of charge produced along the track one can estimate dE/dx and therebay constrain the mass of the particle that produces it.

RTPC Penetration

Energy Deposited in each layer of material as initial spectator momentum is varied.

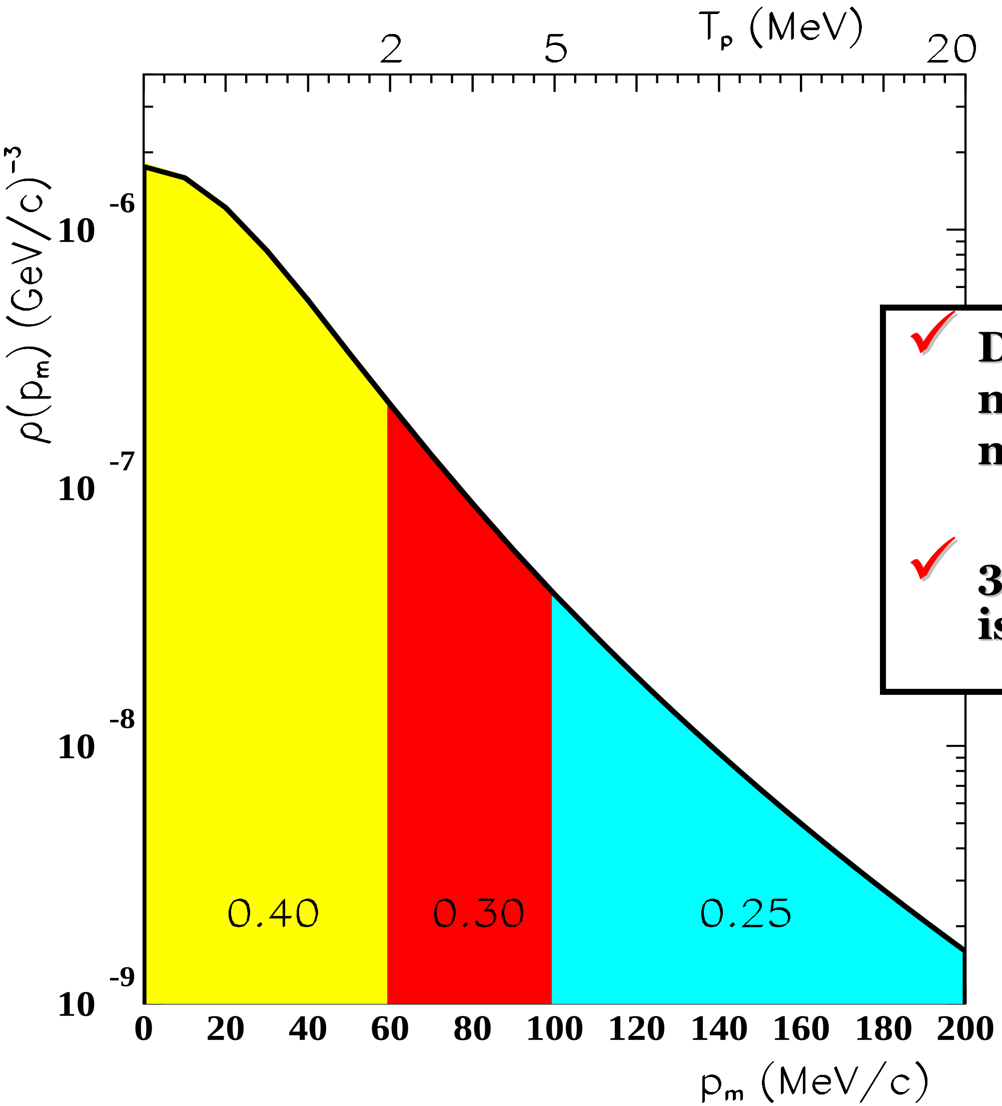
GEANT model





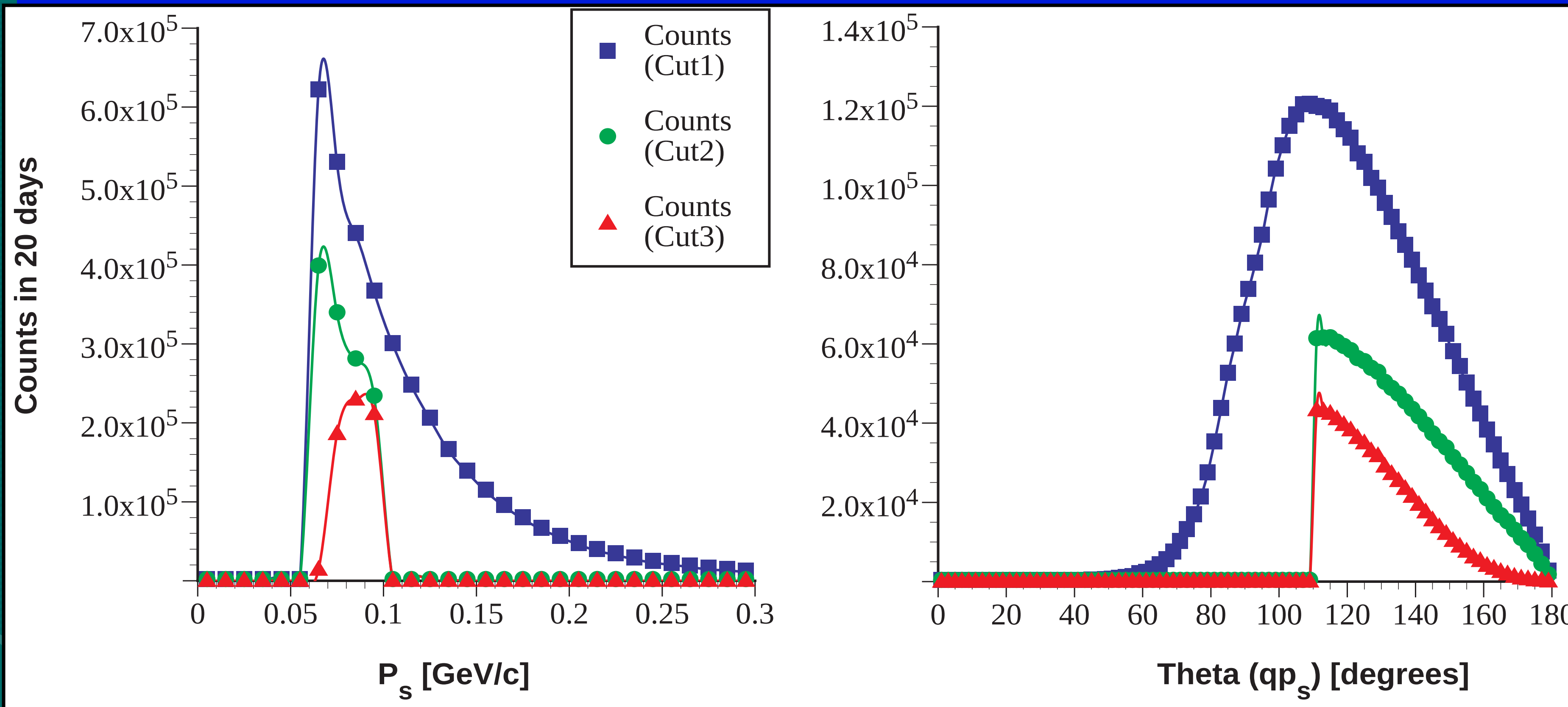
Will measure 70 < p_{proton} < 200 MeV/c

Very Important Protons



- **Deuteron ~ free proton + free neutron at small nucleon momenta**
- **30% of momentum distribution is in chosen p_s range**

VIPs at 6 GeV

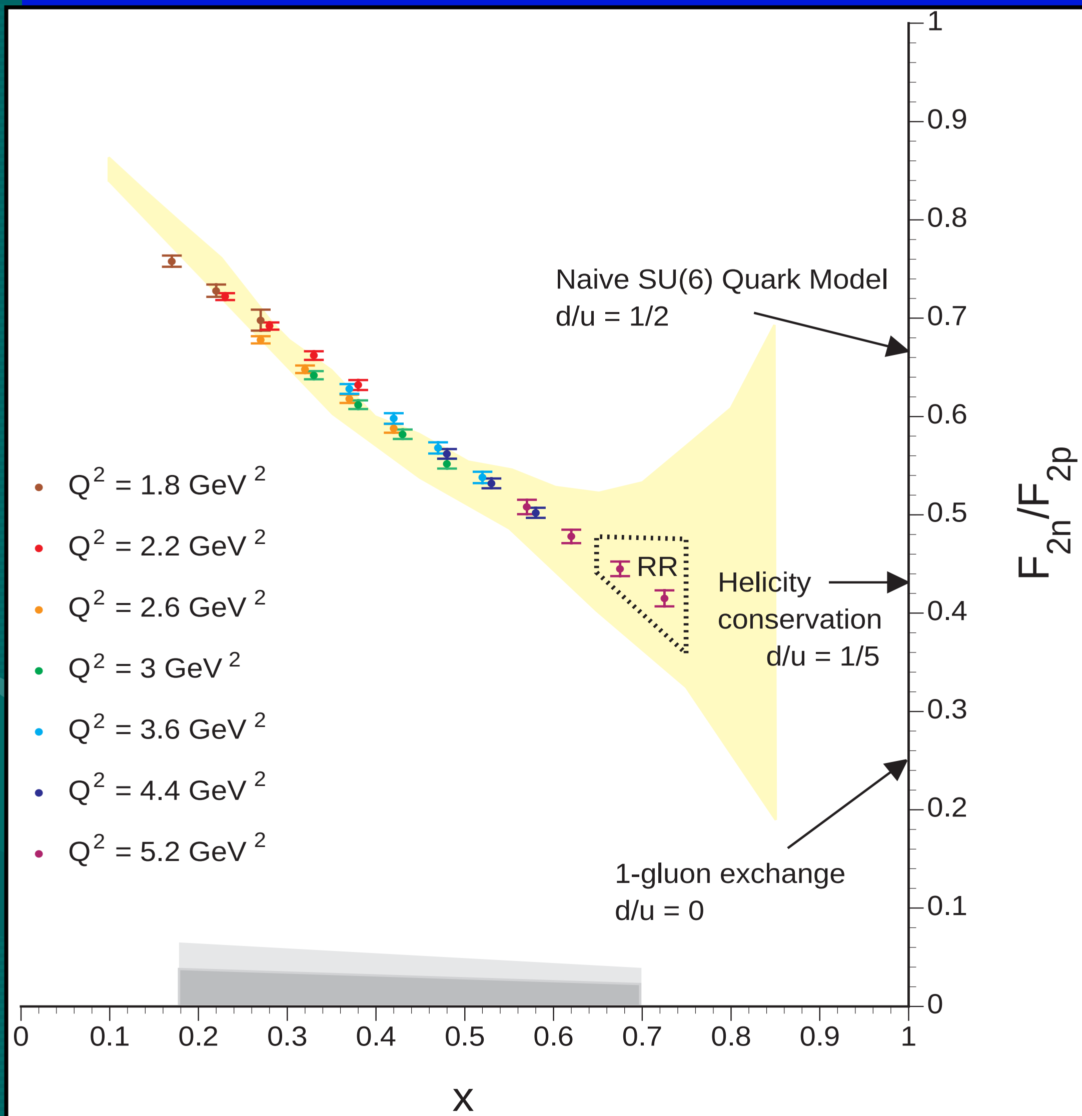


Cut 1: Electron in CLAS, p_s > 60 MeV/c

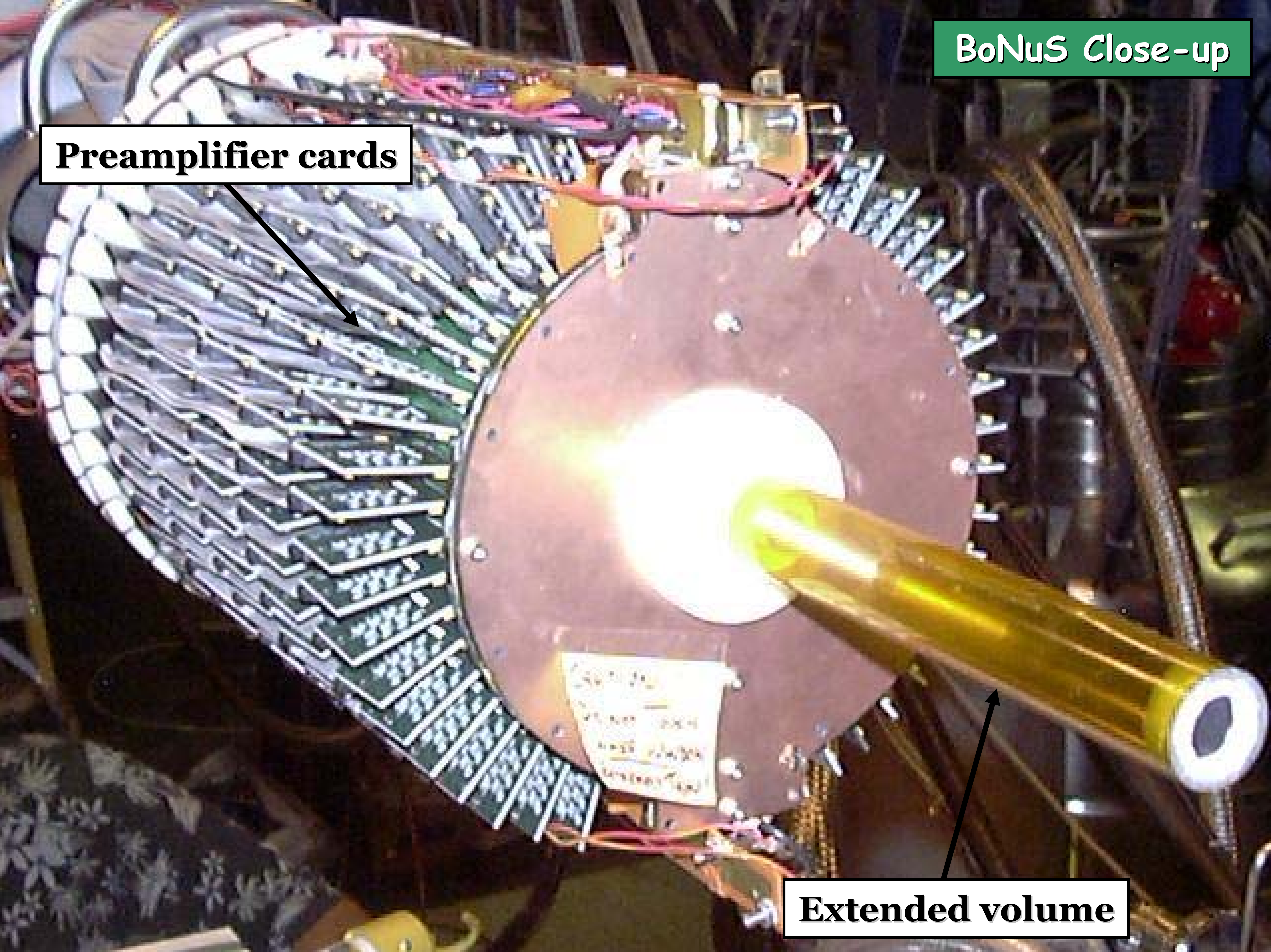
Cut 2: Cut 1 plus p_s < 100 MeV/c, $Q_{pq} > 110^o$

Cut 3: Cut 2 plus spectator in acceptance of recoil detector

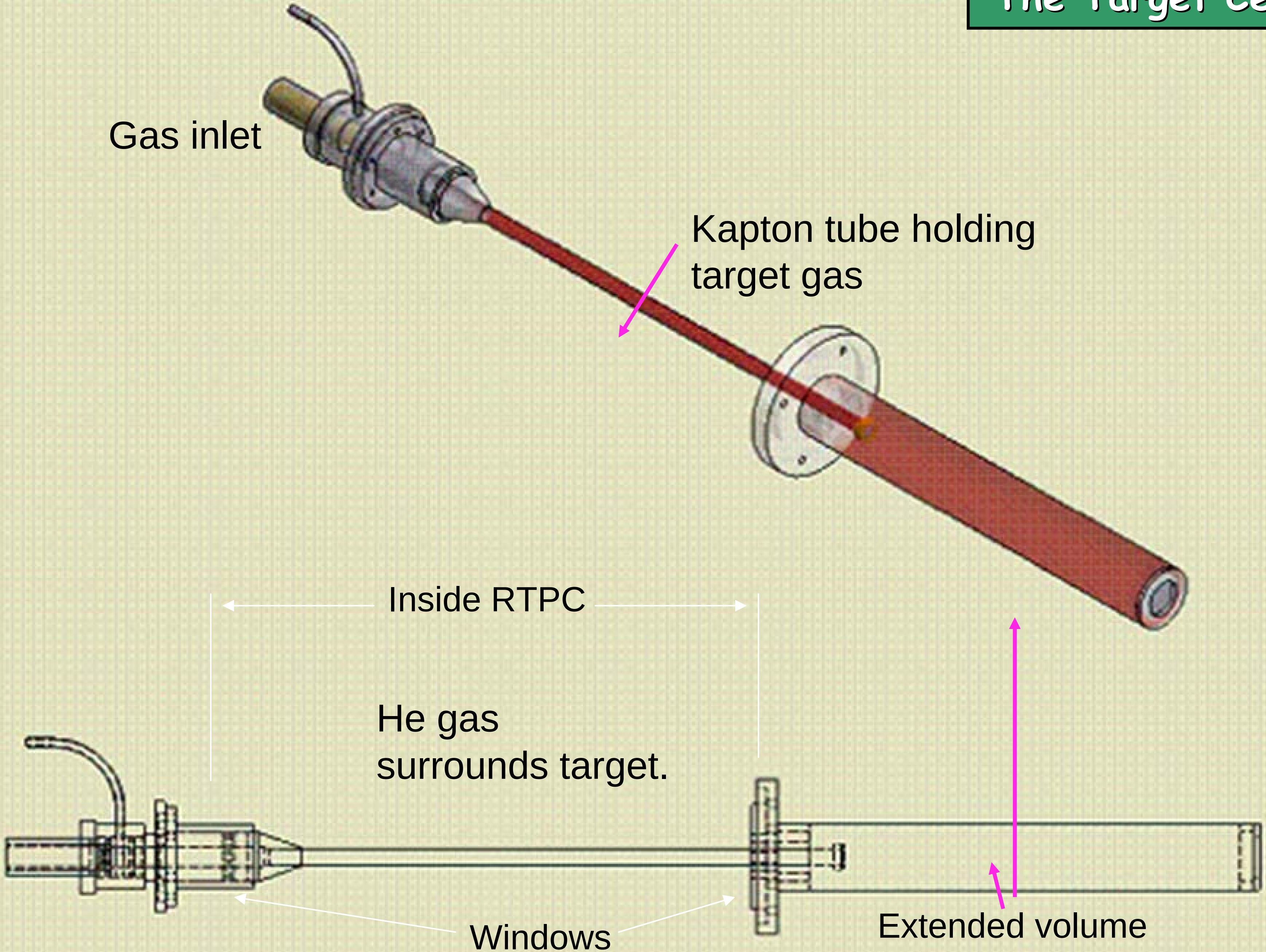
F_2^n / F_2^p (d/u) Ratio at Large x – Projected Results



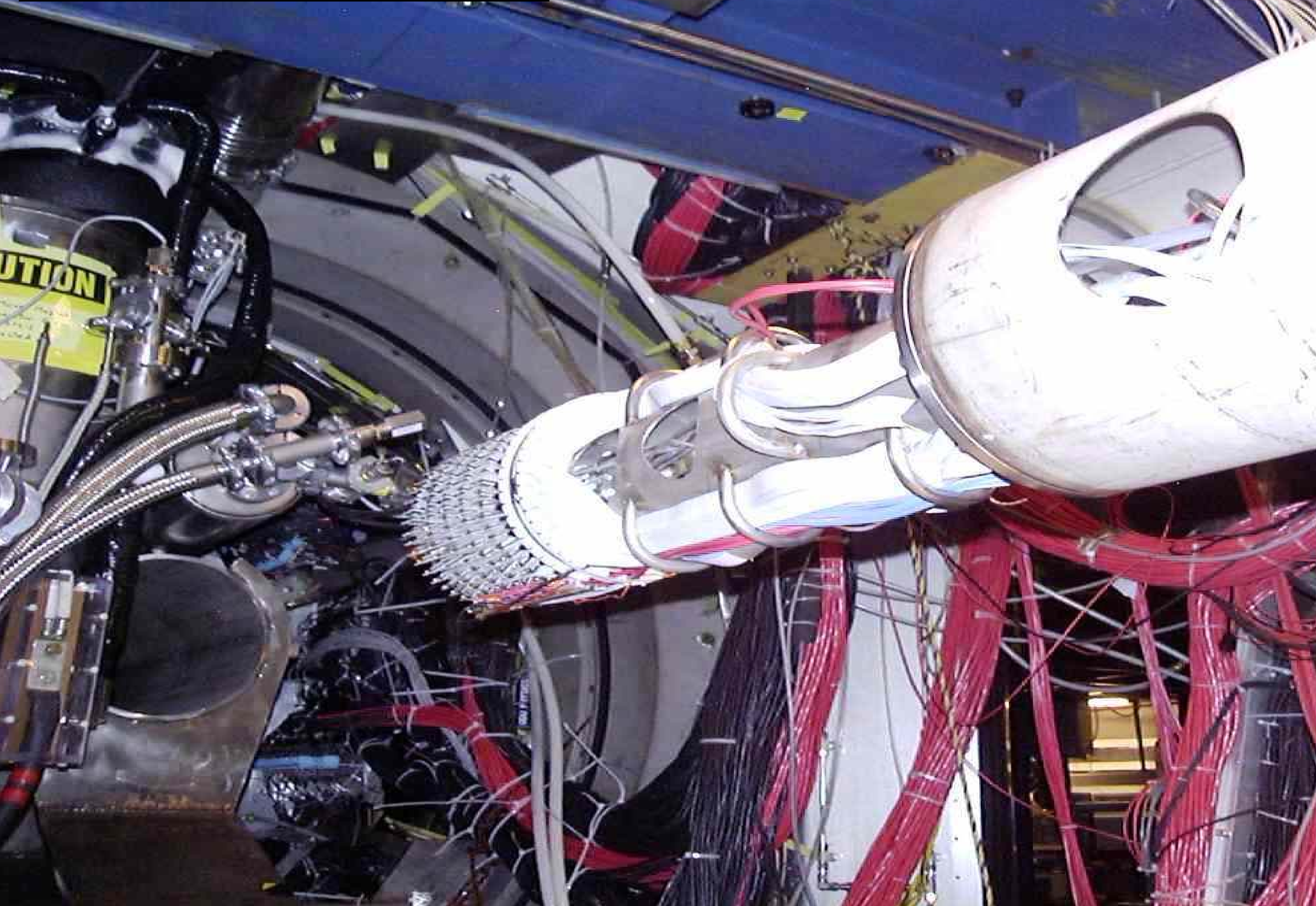
- Yellow shaded area represents current theoretical uncertainty
- RR data begin the Resonance Region
- (W^2 > 3 GeV^2, Q^2 ~ 5)
- Gray shaded areas represent systematic uncertainty
  - Light = total
  - Dark = normalized, point-to-point


BoNuS Close-up
Preamplifier cards
Extended volume

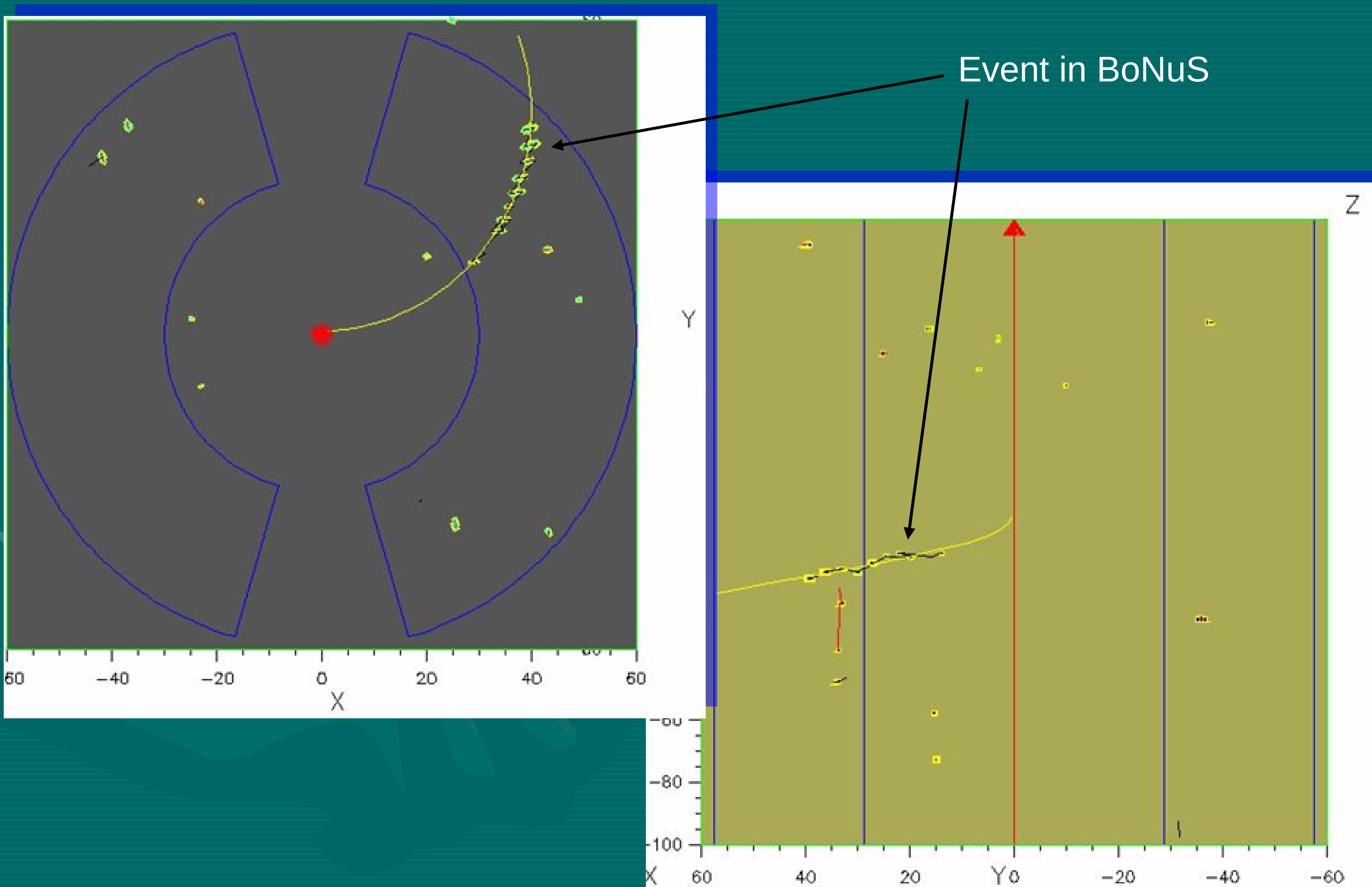
The Target Cell



Installing BoNuS into CLAS

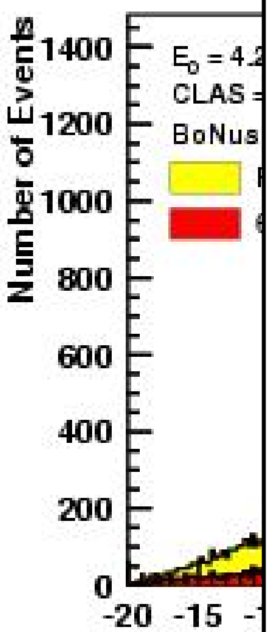


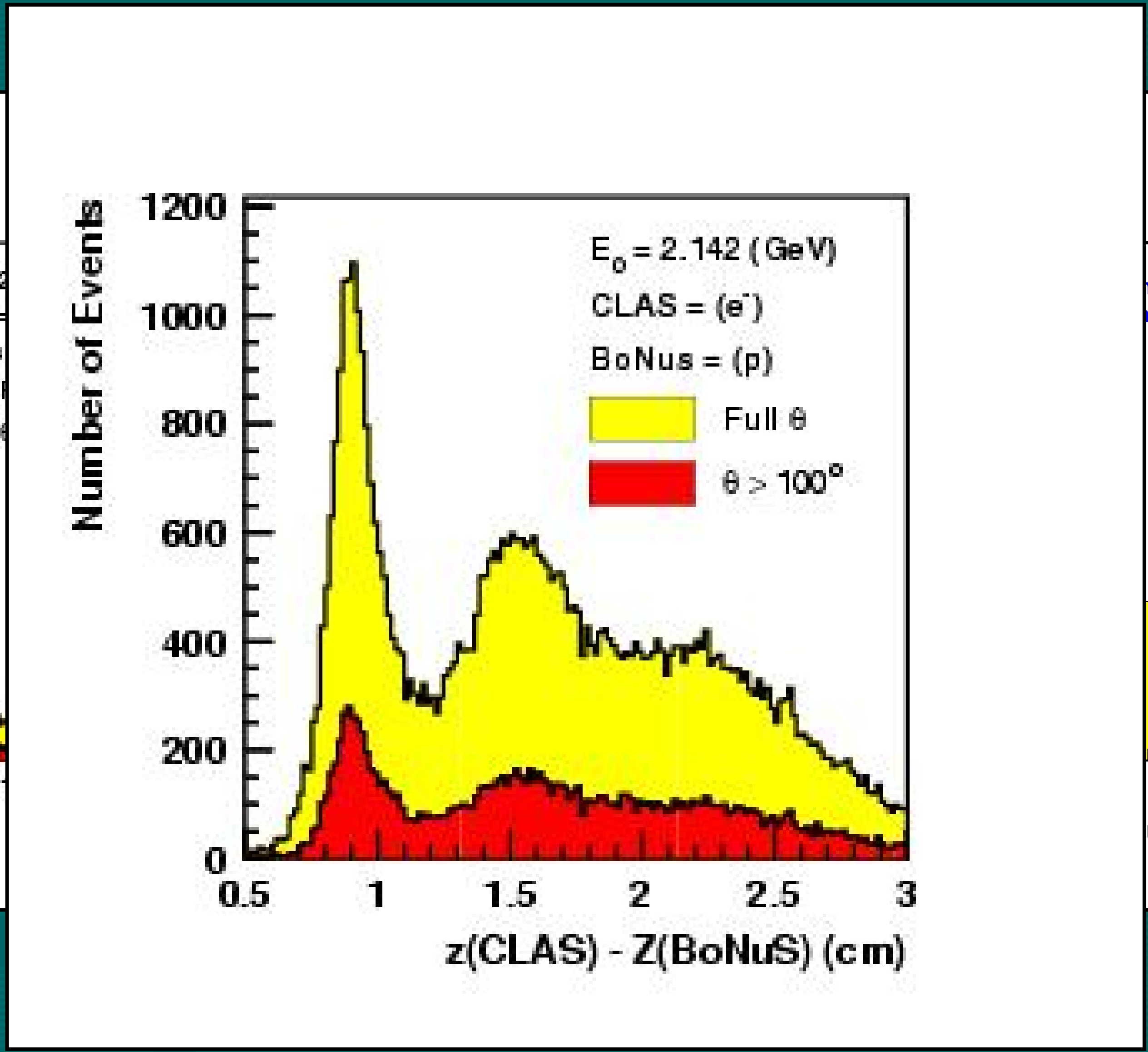
Tracks from BoNuS

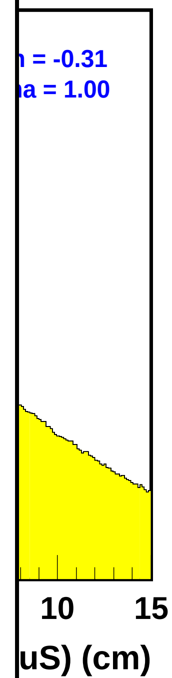


Distributions ....

NEW



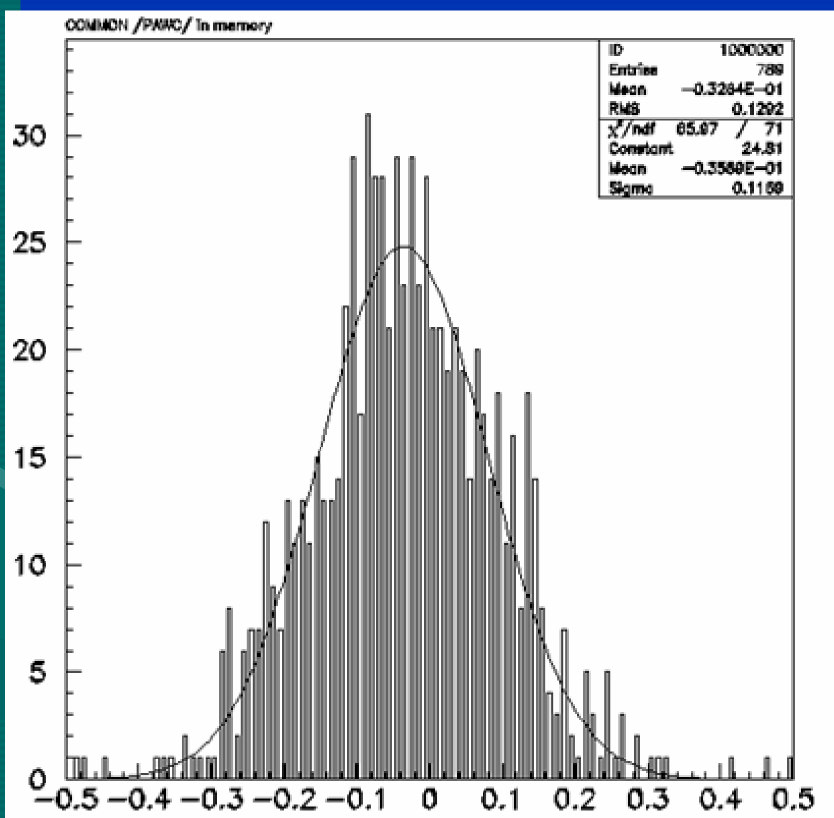




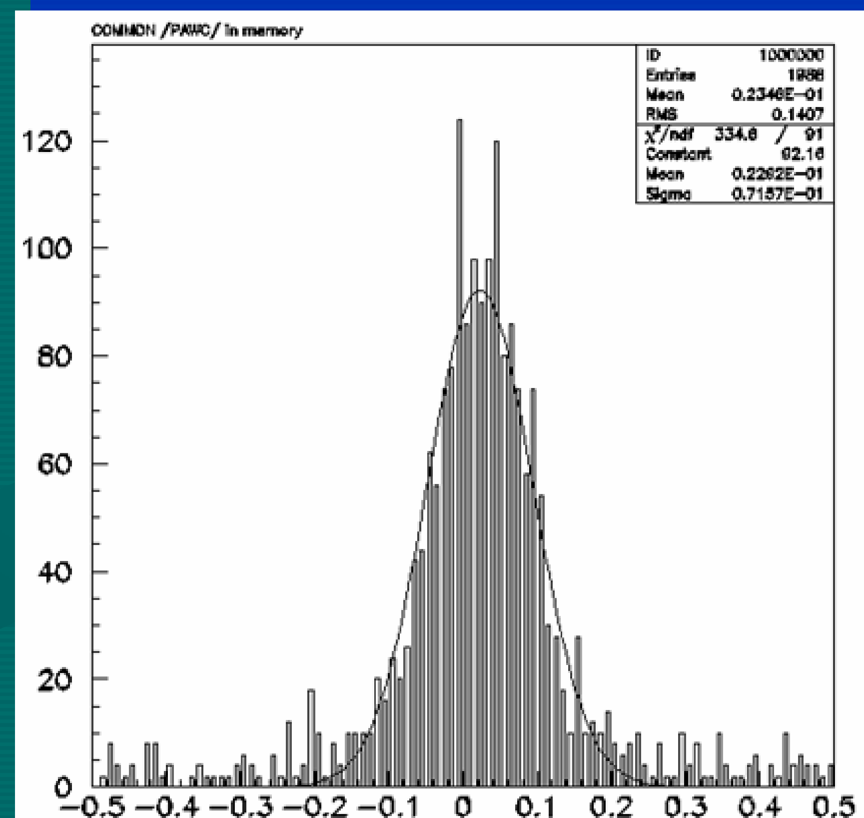
Proton scattering angle; cross-check with CLAS

1.1 GeV Hydrogen

Entries



Ψ CLAS – ψ BoNuS in (radians)



θ CLAS – θ BoNuS (radians)

Summary

- ☺ Elastic form factors
- ☺ Resonance structure
  - Transition form factors
  - Quark-hadron duality
- ☺ Data over a *range* of Q^2, x
  - Structure function moments
  - Large x nucleon structure

Experiment is finished……

Physics Motivation (Neutron Resonance Structure)

Almost nothing is known about the nature of the resonance excitations of the neutron !!!

The extracted neutron - Δ^0 transition form factor appears to be consistent with that of the proton - Δ^+ within the rather large uncertainties, and should therefore exhibit the same anomalous behavior seen in the proton data. Indeed, this would be expected for a pure Δ resonance contribution (and in fact for any isospin I = 3/2 excitation) in the limit of zero width, as isospin conservation constrains I = 3/2 amplitudes for the proton and neutron to be identical. In practice, however, a finite width together with tails from other resonances give rise to a non-resonant background, and even though it is smaller for the $\Delta(1232)$ than for higher mass resonances, it will differ for the proton and neutron. A difference between $p \rightarrow \Delta^+$ and $n \rightarrow \Delta^0$ transition form factors would therefore provide the first hints about the isospin structure of the non-resonant background. For I = 1/2 transitions, on the other hand, such as to the Roper resonance or the negative parity $S_{11}(1535)$, measurement of the electro-excitation of the neutron would allow the first determination of the isospin dependence of resonance production.